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Lessons from Stealth for Emerging Technologies

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Introduction

On the moonless night of January 17, 1991, seven aircraft appeared in the skies over Baghdad. The aircraft were F-117As, better known as Stealth fighters, and they were part of the opening salvo of Operation Desert Storm. Iraq had a formidable radar-based air defense system, but its defenses could not detect the F-117s. Stealth aircraft decimated Iraqi targets during the Gulf War, and no Stealth aircraft were shot down.

Stealth technology—the ability to reduce an aircraft's radar signature by several orders of magnitude—is one of the most important developments in military aviation in the last 50 years. Stealth gave the United States overwhelming air superiority; instead of needing dozens of aircraft to strike a single defended target, a single Stealth aircraft could destroy multiple targets. Stealth's performance in the Gulf War also demonstrated U.S. technological preeminence. If the United States could make aircraft undetectable by radar, what else could it do? Stealth represented a gauntlet thrown down to potential economic and military competitors: they would have to match the United States' seemingly boundless ability to generate new technologies or fall behind.

Thirty years later, the technological and strategic context has changed in many respects, and there is renewed interest in understanding the source of emerging technologies. Stealth was a prime example of the United States' ability to field emerging technologies with decisive results, and its origins can help show how the country produced one emerging technology in the past and how it might produce others today. This paper will use the history of Stealth to identify several lessons for technological development that may help guide current policymakers to specific opportunities, taking into account what has changed—and what has not—in today's strategic environment.

The Origins of Stealth

Literature on strategy and policy at times treats technology as a *deus ex machina*: a new weapon—the longbow, the machine gun, the atomic bomb—appears on the scene and revolutionizes warfare. But why did the weapon appear at that particular time and place? Why not earlier, or later? Why did one side get it, and not the other? To answer these questions, one needs to trace the multiple streams that feed into a technology, and to understand the broader watersheds, the scientific and technological topography, that give rise to those streams. And that, in turn, requires a deep understanding of the science and technology of a particular time and place.

Stealth emerged in the United States in the 1970s because of both strategic pull and technological push.[*] For strategy, the long seesaw between air defense and offense, going back to World War I, had swung decisively in favor of defenses by the early 1970s. This was due largely to radars of increasing range and resolution that could detect and track aircraft hundreds of miles away. In either a full-scale ground war in the European theater or a nuclear attack against the Soviet Union, U.S. aircraft seemed to stand little chance against radar-guided air defenses. The experience of U.S. air forces during the Vietnam War and Israel's in the 1973 Arab-Israeli War, when Soviet-made air defenses decimated American-made attack aircraft, spurred a search for a new approach to the air defense problem.

Several streams in the science and technology watershed offered promise. One was materials. After the advent of radar during World War II, the United States and other combatants pursued radar absorbing materials to diminish the scattering of radar waves from airplanes. The United States continued this research in the

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[*] This account draws on and extends the analysis of Peter Westwick, *Stealth: The Secret Contest to Invent Invisible Aircraft* (New York: Oxford University Press, 2020), which has further details and sources for all that follows unless otherwise noted.

Cold War, and some aircraft—most notably Lockheed's SR-71 reconnaissance aircraft—used radar absorbing materials.

Materials, however, were not as important in reducing radar detection as the shape of the aircraft. Two streams proved crucial to the shaping problem. The first was radar physics. Physicists had long studied the diffraction of light, sound, and water waves around objects, and the emergence of radar drove a substantial, sustained effort on radar diffraction in the United States starting in the 1950s. This program in radar physics developed increasingly sophisticated mathematical theories along with experimental tools for measuring radar scattering. It applied these theories first to simple bodies such as plates, cylinders, and cones, which encouraged their first practical application, in the 1960s, to ballistic reentry vehicles. The first Stealth aircraft, in other words, were spacecraft.

The other major stream was electronic computers, which were increasing in power and decreasing in size and cost. Computers proved crucial in two respects: first, in aircraft design, to calculate the radar scattering from a particular aircraft configuration. Radar physicists could model an airplane as a collection of simple shapes, but to solve the equations entailed immensely complex and laborious calculations. The aerospace firms behind Stealth had thus developed in-house libraries of computer codes for radar scattering. The second use of computers was in flight control. Making aircraft stealthy often made them aerodynamically unstable, and correlating the inputs from flight sensors to maintain stable flight often required reactions faster than a human pilot could make. NASA and the U.S. Air Force for over a decade had supported research in computer-based flight controls, known as fly-by-wire, and the Stealth program capitalized on it.

In 1974 the Defense Advanced Research Projects Agency (DARPA) and the U.S. Air Force merged these various technologies and disciplines in what became known as the Stealth program. The agencies sought to decrease by a factor of 10 the distance at which Soviet radars could detect U.S. aircraft. Since the radar cross-section of an aircraft varies as the fourth power of the range, decreasing the detection distance by a factor of 10 meant decreasing the cross-section by 10 to the fourth, or 10 thousand. An aircraft that was physically 1/10,000th the size of existing planes would be the size of a gnat. Instead, the Stealth program sought to use materials and shaping to keep planes essentially the same size but minimize the radar scattering. The engineering goal, to improve a technological capability by 10 thousand times, measured the audacity of the task.

The DARPA and Air Force program led to three different Stealth aircraft, designed and built by two different aerospace firms, Lockheed and Northrop. An initial contest resulted in Lockheed winning the right to build the prototype of a small attack aircraft, named Have Blue, and then the production version, the F-117. Northrop received a smaller contract, for a prototype battlefield surveillance aircraft called Tacit Blue, of which only one was built. Another contest for the design of a strategic bomber resulted in Northrop winning the contract for the B-2 in 1981.

Lessons of Stealth

With this brief background as a guide, venturing deeper into the history reveals several general observations about emerging technologies. In this section we will explore these nine broader lessons, which apply beyond the specific case of Stealth. The ensuing section will then connect these lessons to current policy issues, in the process considering why these insights remain relevant and how policymakers might capitalize on them.

Strategic implications: unintended consequences and strategic inertia

The scientists and engineers working on Stealth recognized the magnitude of their technological breakthrough. The strategic implications were not as immediately clear; they were emerging alongside, or in some senses behind, the technology.

From 1973 to 1975, the same time the Stealth program got underway, DARPA and the Defense Nuclear Agency convened a series of seminars under the name Long Range Research and Development. The LRRD workshops undertook a fundamental reconsideration of conventional weapons. Smaller, faster, and cheaper computers and sensors were making it possible to identify and strike targets accurately, and precision conventional weapons might allow the U.S. to counter a Soviet attack on Western Europe without using nuclear weapons. The new conventional weapons also put a premium on survivable delivery systems, which set the table for Stealth.

Subsequently, in the Carter administration, Defense Secretary Harold Brown and Undersecretary of Defense for Research and Engineering William Perry (in the office originally known as director of defense research and engineering, DDR&E[*]) embraced an "offset strategy." With the United States and Soviet Union at rough parity in nuclear weapons, and with the Soviets enjoying a numerical advantage in conventional weapons, the United States would turn

[*] The office changed names several times over the years; for simplicity we refer to this office and its successors simply as DDR&E.

to emerging technologies to offset Soviet strengths and regain the upper hand. Brown and Perry viewed Stealth as part of this offset strategy.

Some of the broader implications of Stealth, however, emerged after the program was conceived and underway—and some of those implications were perceived not by the United States, but by the Soviets (who, after all, favored grand theories). Soviet military theorists integrated Stealth with precision-guided munitions in the concept of a "reconnaissance-strike complex," part of a wider Military-Technical Revolution. This revolution, Soviet planners perceived, overturned existing assumptions about how wars would be fought. The concepts that coalesced in the United States in the 1990s as the Revolution in Military Affairs (RMA) were developed by Soviet strategists in the 1970s.[1]

The Soviet perception of Stealth's revolutionary import compounded its strategic effect, and was an unforeseen consequence. As U.S. analysts picked up on the Soviet response, they recognized more fully the implications, in particular for nuclear doctrine. They pursued these ideas in another series of workshops starting in 1982 that included an explicit sequel, called LRRD II, to the early 1970s workshops. LRRD II viewed Stealth as one of five high-priority technologies, alongside precision-guided munitions and sensors, driving a military revolution.

The theorizing included fundamental reconsideration of the role of nuclear weapons. One analyst at the time summarized the shift. In general, there were two ways to destroy a target: a small bomb close to the target, or a big bomb not so close to the target. During the Cold War, the United States had relied on the big-bomb approach, but the ability to deliver conventional weapons with pinpoint accuracy meant the United States didn't need to use big bombs, because small ones would do. The new technologies of Stealth and precision weapons, the analyst declared, made nuclear weapons "both wasteful and irrelevant."[2]

In the speech announcing what became known as the Strategic Defense Initiative in March 1983, President Reagan announced the goal of making nuclear weapons "obsolete." In fact, some analysts argued, it was not missile defense but Stealth and precision weapons that could make nuclear weapons obsolete. This reasoning, elaborated by Albert Wohlstetter and others, culminated in the *Discriminate Deterrence* study, begun in 1986. The report declared that Stealth and precision weapons "will enable U.S. to use conventional weapons for many of the missions once assigned to nuclear weapons."[3]

By that time, however, the B-2 was well into production as a strategic bomber. In the end the doctrine of nuclear deterrence had too much inertia, and the Military-Technical Revolution failed to overcome the technological, organizational, and intellectual commitment to nuclear weapons.

In short, the example of Stealth shows that the strategic implications may not emerge until after the technology; that an adversary may perceive them more clearly than the technology's developer; and that emerging technologies may fail to overcome the inertia of existing doctrine.

Blue-collar technology and the shop floor

It is one thing to conceive a new technology, another thing to build it. Consider nuclear weapons. Scientists around the world recognized in 1939 that a nuclear weapon was possible, but it took the United States and its allies a vast effort over several years to actually build one. The design principles now are well known, but the manufacturing challenges have kept many countries from acquiring them.

Consider also machine guns, where the concept was familiar long before manufacturing techniques of both ammunition and guns enabled their production. Closer to our time, manufacturing capability was a primary factor in building ultra-quiet submarines. The United States discovered that even with an ultra-quiet design a submarine would be noisy if the shipyard failed to provide strict quality control—and the Soviets apparently struggled to enforce the necessary quality in their shipyards.[4]

Other nations have similarly struggled to achieve the manufacturing capability needed to replicate Stealth.[5] Even after design engineers had an aircraft plotted on blueprints, someone had to turn those drawings into flying hardware. Kelly Johnson, the legendary founder of Lockheed's Skunk Works, declared that even if you gave the blueprints of the SR-71 to the Soviets they couldn't replicate the aircraft; they didn't have the ability to cut, shape, and weld titanium.[6] Johnson recognized that there is another side of engineering: the shop floor, where machinists and manufacturing engineers practiced what Wernher von Braun liked to call "dirty-hands engineering."[7] The shop floor was a different world from the offices of design engineers: a blue-collar site of drop hammers, rivet guns, hydraulic presses, autoclaves, and lathes. But it was as important as a source of innovation.

The inventiveness of Stealth designers would have gone for naught had the shop floor workers not matched it. How to make the faceted panels of the F-117 or the complex curvatures of the B-2? Do you cast them, machine them, form them? How do you ensure structural integrity of the surface? How do you achieve the unprecedented tolerances required? Then there were the temperamental radar-absorbing materials, many of which changed characteristics at different temperatures, pressures, and humidity levels. As a Lockheed shop-floor manager put it, it was as if the materials had a metabolism—they were more like a living creature than an inert hunk of matter.[8]

Both Lockheed and Northrop succeeded at Stealth by integrating design and production engineering, keeping both parts of the process in constant contact. Designers and production staff worked in the same facility, creating a collaborative environment where the workers building an aircraft could talk directly with designers, telling them when certain designs couldn't be physically built, or couldn't be built for the allocated cost.

The role of scientific and engineering disciplines in new technologies

Science and engineering disciplines shape the creation of new technologies. Disciplines provide a sort of inertia, with institutions (such as university departments and scientific societies) and pedagogy (textbooks and syllabi) designed to propagate but also perpetuate existing approaches. In the case of Stealth, the radar physicists pushing the new approach contended with aeronautical engineers steeped in traditional precepts of aircraft design. At Lockheed, Skunk Works stalwarts (starting with Kelly Johnson) insisted that aerodynamics, not radar physics, was the primary driver of aircraft design. That insistence had suppressed earlier efforts at Stealth at Lockheed, and it threatened to derail the firm's efforts when the program got underway. Only by putting radar experts explicitly in charge did Lockheed managers overcome this resistance. Northrop meanwhile allowed aerodynamic traditionalists to retain a stronger voice, and as a result its initial design represented a compromise between aerodynamics and radar—which resulted in Northrop losing the initial competition that led to the F-117.

Similar disciplinary dynamics over a new technology appeared for missile defense in the 1970s and 1980s, where physicists and software engineers viewed its prospects through different lenses.[9] To change the metaphor, science and engineering disciplines can provide a sort of friction, an additional resistive force that must be overcome by emerging technologies. Careful attention to this friction can ensure that established disciplinary interests do not impede new technologies.

Competition as spur to innovation

The different disciplinary relationships at Lockheed and Northrop highlight another lesson of Stealth: competition as a spur to innovation. DARPA and the U.S. Air Force from the outset explicitly encouraged competition, which produced a fierce but friendly rivalry between the two firms. Northrop's John Cashen quipped that his enemy wasn't the Soviet Union; it was the Skunk Works.

Ben Rich, who had succeeded Kelly Johnson as Skunk Works director, liked Cashen's attitude and reciprocated it.

The competition resulted in different approaches, which are apparent in the remarkably distinctive appearance of the aircraft. Lockheed's flat, faceted F-117 looks like flying origami, while Northrop's B-2 is curved and sleek. Competition, in other words, produced two very different solutions to the same problem. In order to design aircraft that could evade radar detection, Lockheed employed flat surfaces and Northrop embraced curved ones. These approaches reflected the particular experience and disciplinary balance of each firm. Northrop did not allow radar experts to control the design, as they did at Lockheed, which gave aerodynamicists a stronger voice—and those aerodynamicists preferred curves. The curves hurt Northrop in the F-117 contest but helped on the B-2, which required greater aerodynamic performance for the long ranges essential to its mission. Northrop's shortcomings on the F-117 thus turned into an advantage on the B-2. Competition allowed the weaknesses and strengths of each side to play out in the long run.

There is, again, an analog in the nuclear weapons program, where the Atomic Energy Commission created the Livermore weapons lab to provide competition to Los Alamos and encourage different approaches.[10] One might say that competition is the American way, but we see similar competition, also consciously encouraged, in the Soviet nuclear and missile programs. In both countries competition entailed costly duplication, but the cost was deemed worth the rewards.

DARPA and the Air Force kept the two teams strictly isolated, with no interchange between them, but there was one exception to this stovepiping in the Stealth program and it proved crucial. Lockheed's designers at one point considered a flying wing—that is, an aircraft that is all wing, without an extended fuselage—for what became Tacit Blue. DARPA managers awarded that program to Northrop, but they were intrigued by Lockheed's proposal and dropped hints to Northrop's team that they consider a flying wing. In the end Northrop went with a different layout for Tacit Blue, but the flying wing concept stuck with them—and they used it on the

B-2. The flying wing idea, in short, crossed between the stovepipes. The episode demonstrated the need for subtle discretion by program managers—which leads us to the next lesson.

The importance of mid-level program managers

The initiative for the Stealth program did not come from the top down, from presidents or generals operating from a grand-strategic vision, or from the bottom up, from the soldiers (or, in this case, pilots) who would be the ones to wield the new technology. The initial push came rather from technical managers in the Air Force, DARPA, and DDR&E. The role of those managers highlights the importance of science and engineering expertise within the military.

The U.S. military historically had such expertise; West Point, after all, is an engineering school, and there had been technically savvy officers such as Hap Arnold in the Army Air Corps. The Cold War, however, hugely boosted the presence of technical experts within the military services and the U.S. Department of Defense (DOD). The Air Force began sending young officers to graduate school for advanced training in science and engineering; one of them, Lew Allen, earned a PhD in nuclear physics in the early 1950s, and 25 years later he was chief of staff of the Air Force, the first to reach that position through the technical branches. He was joined by an unprecedented assembly of expertise in President Carter's Defense Department, up to and including Defense Secretary Harold Brown, a Columbia physics PhD and the first professional scientist to hold the position.

These scientists and engineers not surprisingly welcomed technological solutions to strategic problems, and the top-level appointees supported and encouraged the mid-level program managers who initiated Stealth. In general, mid-level program managers serve as crucial mediators between the fields of science and technology on the one hand and strategy and policy on the other. They translate technological opportunities and challenges into strategy and policy, and vice versa. These scientists and engineers may provide technological options to resolve complex strategic or policy problems, but there is a potential hazard: they may foster reliance by higher levels only on technological solutions to such problems, and they may thus encourage neglect of political or diplomatic solutions such as arms control.

Need for long-term investments

In a large watershed it takes time for rainfall to run off hillsides, collect in rivulets and streams, and eventually feed into big rivers. Emerging technologies similarly take time, often several decades of sustained effort.

The payoff for Stealth arrived in the 1980s and 1990s, but the commitment started in the 1950s, when the Air Force (and, later, DARPA and the Army missile defense program) began supporting research in earnest on radar-absorbing materials and, more importantly, both the theory and measurement of radar scattering. Early investments in theory research, especially in university labs at Michigan and Ohio State, resulted in a sophisticated mathematical description of radar scattering. The experiments meanwhile developed an understanding of how to measure radar scattering, and how slight variations in the experimental setup could lead to large differences in data. The Air Force built sensitive radar test ranges, most notably at the Radar Target Scatter site (RATSCAT) at White Sands Missile Range, which had an array of antennas capable of generating radar at various frequencies and polarizations and then detecting the radar waves scattered from a model aircraft even to vanishingly low levels.

The long-term commitment extended to the firms themselves. In the early 1960s, for example, Northrop formed a group on radar physics using in-house discretionary funds; a decade later the company had a thriving group of theorists deeply versed in radar scattering. The investments, in other words, paid off not just in technologies, theories, and facilities; they also paid off in human capital. Both the firms and the agencies behind Stealth by the early 1970s had a cohort of engineers who understood what the technology could and couldn’t do.

Stealth technology required the patient development of the fields of radar physics and radar engineering. Military managers did not support this effort with the expectation of a specific breakthrough of the magnitude of Stealth. They did so rather in a more general belief that radar was important to warfare and that the military would benefit from understanding it better. Similarly, physicists in the 1910s and 1920s did not work on atomic and quantum theory in the belief that it would lead to nuclear bombs. In both cases, eventual breakthroughs obscured the decades of incremental advances that preceded them. The case of Stealth highlights the need for enlightened program management, for the judicious support of fields that seem esoteric but can nonetheless have substantial long-term payoffs.

Public-private collaboration

Stealth resulted from investments by both public agencies and private firms, and the program itself was a collaboration between the Air Force and DARPA on the government side and Lockheed and Northrop in the private sector. In the Cold War struggle to demonstrate the superiority of free enterprise against a command economy, the United States relied not on an unfettered free market, but rather on a tight integration of the state and private industry.

President Eisenhower, in his farewell address in January 1961, warned that the "military-industrial complex" represented a dangerous incursion by the state into private enterprise and by private interests into public policy. Stealth, however, provides a more positive view of the civil-military, public-private collaboration.[*] People who worked in the Stealth program, whether in DARPA, DDR&E, and the Air Force on the one side, or Lockheed and Northrop on the other, universally praised the sense of teamwork between the public and private sector, and between the military and the civilian contractors.[11]

This does not mean the two sides always agreed, or that their interests perfectly aligned. The leadership of both firms strove to

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[*] The term "public-private partnership" has acquired a formal connotation, often in connection with infrastructure projects, and I will avoid it here.

maximize profits and feared commitments that would expose their respective companies to financial risk; government managers meanwhile sought to ensure political oversight and accountability. On the B-2, for example, Northrop engineers complained that the constant scrutiny of government auditors distracted them from the difficult technical problems, while political representatives criticized cost and schedule overruns. This is nothing new; one can find complaints by contractors about government meddling and by federal agents about corporate profligacy during World War II, and earlier. At the working level, however, each side respected the technical competence of the other; they shared the language, culture, and values of engineering—again, a benefit of having technical experts as program managers. One consequence of this measure of trust was a willingness to communicate informally, for instance through personal conversations rather than memos, which helped cut time and cost.

International origins of key ideas

Stealth did not just derive from scientists and engineers at Lockheed and Northrop, or in DOD-sponsored labs. A major contribution came from the United States' main adversary in the Cold War. Pyotr Ufimtsev, a physicist in the Soviet Defense Ministry's main radar institute, found a way to account for gaps in the existing theory of radar scattering, and his theory found its way to Stealth's designers through a U.S. Air Force program to translate Soviet technical literature. The American teams, especially at Northrop, recognized it as a major breakthrough and incorporated it into their approach.

Historians have long recognized that many technologies have international roots.[12] Gunpowder, for instance, originated in China before its wide circulation across Europe. Closer to our times, the x-ray laser, a centerpiece of President Reagan's Strategic Defense Initiative, drew key concepts from the attendance by a Livermore physicist at a Soviet laser conference.[13] Nuclear weapons offer another example. The Manhattan Project had key contributions from British scientists and European Jewish emigrés, not to mention the training in quantum and nuclear physics that many U.S. scientists had received in European universities. Soviet nuclear scientists had similarly benefited from education in European universities; China benefited from Soviet advisors; and so on.

The diffusion of science and engineering knowledge is sometimes an incidental product of the international scientific community. In the case of Stealth, it occurred because Ufimtsev published his research in the open Russian-language literature, and U.S. colleagues happened to run across it through open source intelligence collection and translation. (And Ufimtsev in turn was keeping up with unclassified research on scattering theory in American technical publications.)[14] Some international scientific exchange, however, is deliberate, such as the revival of the international science community after the nationalist divisions of World War I. As this example suggests, scientists and policymakers have at times viewed the benefits of scientific exchange as not simply scientific or technological—and not strictly reciprocal. For example, the United States established formal science exchanges with the Soviet Union in the 1950s and China in the 1970s. It did so even though it recognized that Soviet and Chinese scientists lagged U.S. colleagues in many fields (especially in China, where the Cultural Revolution had devastated science) and had more to gain from exchanges.

The United States supported these science exchanges, in part, to obtain scientific intelligence, to avoid Sputnik-like surprises; in part to use scientists as a channel for arms control; and in part to use science as a way to bridge political differences and provide mutual understanding. This last motivation often included the belief that science had a liberalizing influence on authoritarian regimes, bending them on a long arc toward political alignment with the United States.[15] As Stealth demonstrated, however, international communication could have more immediate, practical payoffs.

The basic point: the science and technology ecosystem does not begin or end at the United States' borders. It extends around the world, with fundamental implications for national security.

The costs (and benefits) of secrecy

The United States wants to make sure its scientists and military know about all current developments wherever they occur—but it also wants to prevent its adversaries from obtaining this knowledge. The U.S. government attempted to install a one-way valve on technical information through its security system. Some of the previous research that fed into Stealth—such as the theory of radar scattering, and the fly-by-wire systems—was unclassified, and the program itself started at the lowest level of secrecy, Confidential. But as the work began in earnest in 1976 the Pentagon re-classified it at the highest level, as a Special Access Program. The United States did not divulge the existence of the Stealth program until 1980; even afterward it kept the details, including the deployment of the F-117, secret for several more years. It finally disclosed the existence of the F-117 in November 1988, seven years after first flight and five years after deployment. (We now know that the United States also waited until late 1985 to reveal the F-117 to its closest ally, the United Kingdom.)

There was good reason for secrecy: the Soviets had a vigorous espionage program to penetrate U.S. aerospace firms, including the Stealth contractors. Secrecy, however, came with costs. In personnel security, investigating employees for a high-level clearance could run tens of thousands of dollars and take several weeks or months; during that time employees got paid but could not work on Stealth. Then there were the costs of physical security, such as safeguarding classified facilities and storing and tracking classified documents and computers. Security added perhaps 15 percent to the cost of the B-2, and that did not include less tangible costs. Workers could not share information with colleagues, which hindered progress; on the B-2, for example, classification imposed a barrier between design offices and the shop floor.

Secrecy also had benefits, however. It sheltered the Stealth teams from meddling at several levels. Within both firms, the small groups pursuing Stealth were insulated from the larger bureaucracy. They thus evaded the conservatism that over time tends to calcify even the most innovative institutions, such as the Skunk Works (although even there the Stealth designers did not entirely escape ingrained engineering approaches). At the program level, secrecy fostered efficient management. Lockheed built the initial Stealth prototype in 20 months from contract to first flight, and the F-117 in 31 months. The Skunk Works could work so fast because, as a highly classified program, it didn't have an army of auditors and procurement officers looking over its shoulders. Secrecy also allowed Stealth to avoid political interference. Congress couldn't question the budget or call in program managers to testify in hearings, at least until the mid-1980s, when the B-2's escalating costs attracted political scrutiny. Similarly, during World War II the Manhattan Project's leaders had used secrecy to prevent Congress and other executive agencies from meddling in the work leading to the atomic bomb.[16]

This lack of political oversight was also, of course, a fundamental cost. Democratically elected political representatives did not know basic facts about the Stealth program: not only the design of the aircraft but their budgets and their very existence were kept secret from the public. The Pentagon briefed a few select members of Congress on key defense committees but otherwise kept Congress in the dark; the briefed members had to persuade congressional colleagues that the secret funding was worthwhile.

There was one more cost, less tangible but no less fundamental, on the personal lives of the individuals who invented Stealth. Workers had to undergo intrusive security investigations; over time, they internalized the surveillance, constantly monitoring what they did and said. One retired aerospace engineer, explaining the difficulty he had talking about his job, said, "You have to understand, I spent forty years trying to be a gray face."

The U.S. security system, of course, did not compare to the authoritarian regimes of the Soviet Union or of China today, but it nevertheless took a toll—on the individuals who developed the technologies, on the values of the science and engineering community, and on democracy.

Secrecy did not entirely succeed. The Soviets learned about Stealth by 1975, within a year of the first concept studies, not through sophisticated tradecraft but rather by simply reading the American trade press such as *Aviation Week* (a.k.a. "Aviation Leak"). The Central Intelligence Agency did not entirely mind the leaks. Media accounts often merged fact and fantasy; published estimates of the B-2 radar cross section ranged from 5.0 to 0.000001 square meters, complicating the job of Soviet analysts trying to determine Stealth's capabilities.[17]

The failure of secrecy was useful to the United States in another respect. Wonder weapons cannot deter an adversary if they are kept under wraps. As the fictional Dr. Strangelove said of the Soviets' Doomsday Machine, "the whole point…is lost, if you keep it a secret!" Or, as Reagan's science advisor put it, "there's no deterrence in a black program." In this sense, Stealth was like nuclear weapons, which served their purpose simply by existing. Defense Secretary Harold Brown somewhat cryptically framed the concept at a press conference in 1980 announcing the existence of Stealth: "The potential already has the effect."[18] The strategic function of these technologies was as much their mere existence as their actual use. They acted on the adversary's imagination, not on their armed forces.

The leaks were useful in a final respect: they allowed the Soviets to develop their theory, described above, of the revolutionary impact of Stealth, which opened the eyes of U.S. analysts to the emerging RMA. The RMA concept reinforced the perception of U.S. military dominance—which also served a strategic purpose.

What Has Changed Since Stealth—and What Has Not

Do the lessons of Stealth still hold today? The world has changed since the 1970s. The Soviet Union is long gone, and the Cold War with it. Instead of facing an all-out nuclear exchange or a huge tank battle on the European plain, the United States confronts an array of threats, some of them asymmetric. Some strategists now view Stealth as a relic of an obsolete strategy based on costly, human-oriented systems. Instead of relying on a few hard-to-replace Stealth aircraft penetrating enemy airspace, such observers argue, the U.S. military should deploy swarms of small, cheap, autonomous drones.[19]

Those drones mark another change in the landscape, in technology. Emerging technologies today include artificial intelligence (AI), machine learning, data analytics, cyberwarfare, quantum computing, autonomous vehicles, lasers, and genomics. This crop of emerging technologies is sometimes referred to as a “third offset.”[20] The first offset was nuclear weapons, on which the United States relied during the early Cold War to offset a Soviet advantage in conventional forces. The second offset, starting in the 1970s, was Stealth and precision-guided weapons, again offsetting a Soviet quantitative advantage in conventional weapons (since, owing to nuclear parity, nuclear weapons could no longer serve the offset function). Although the second offset was not a single technology, the third offset is an even more disparate collection, which spreads out the risk of technology development but also greatly diffuses the technological focus.[21] Unlike the first and second offsets, it is not at all clear for the third offset exactly who is the adversary, what is their specific military advantage, and how new technologies offset that advantage. This lack of strategic and technological clarity is a change from the 1970s—and perhaps a reason not to extend the “offset” concept to the current context.

Another apparent change is that many of today’s emerging technologies are dual-use and often come out of the private commercial sector. Stealth and precision-guided munitions had no commercial uses; AI, big data, robotics, and genomics do. Stealth was funded by military agencies and developed by two firms long accustomed to working with the military; the firms associated with today's emerging technologies often lack that experience. Although the U.S. military is currently trying to build relations with firms in Silicon Valley, its efforts are complicated by resistance to weapons work among some tech workers. This shift reaches back to the Vietnam War era and the rise of the counterculture, which had a particular presence in Silicon Valley. The ensuing post-Cold War emphasis on commercial technologies means that many Silicon Valley firms and their employees today are unfamiliar with the military. Most notably, Google pulled out of the DOD's Project Maven on AI after thousands of its employees signed a petition against the project. Military program managers for their part are also less familiar with contractors outside the traditional defense industry, so there is learning required on both sides.[22]

Another change is that high-tech capabilities have spread through an increasingly globalized world. In particular, a primary strategic adversary, China, has its own flourishing high-tech industry, something the Soviet Union lacked. Perhaps the biggest change today thus seems to be that the United States no longer enjoys technological preeminence. There is instead talk of great-power decline and "the end of the American century," amid the rise of economic as well as military challengers. Stealth was a major contributor to the sense of U.S. high-tech dominance, when the nation's triumph in the Cold War and then the overwhelming display of weaponry in the Gulf War conferred a comfortable position as the sole superpower. What commentators describe as Stealth's obsolescence may thus mirror the nation's waning status.

This is not the first time, however, that the United States has seemed in decline. At the time of Stealth's development in the 1970s, the United States was mired in malaise. It had just endured a humiliating defeat by an asymmetric adversary in Vietnam, its economy had both rampant inflation and unemployment, Watergate had undermined faith in the government, the Soviets were seen by some influential observers as eclipsing U.S. military power, and Western Europe and Japan had seemingly surpassed the United States in high-tech industry. The specifics of the decline may have differed from today; the point is that people at the time, as they do now, perceived that the United States had grown weaker in several respects. The response during the so-called "era of limits” was a period of great technological ferment, incubating genetic engineering, the personal computer—and Stealth. The emerging technologies of the 1970s helped drive the nation’s rebound.

The echoes of declinism suggest that although some aspects of the technological and strategic landscape have changed, others have not. Just as the novelty of U.S. decline may be overstated, so too may be the dominant role of commercial firms in today’s emerging technologies. AI, the personal computer, and the internet, linchpins of today’s Silicon Valley, all derived from military R&D going back 50 years.[23] Other technologies associated with the private sector, such as the iPhone, similarly have roots in public funding. Scholars have recently argued against the view that the commercial sector has become the primary source of innovation, highlighting instead the role of the federal government, especially the military, through what has been called “the entrepreneurial state.”[24] Eric Schmidt, the former Google CEO, recently wrote, “We [that is, Silicon Valley] can’t win the technology wars without the federal government’s help.” The fact that Schmidt felt compelled to declare this in a *New York Times* op-ed suggests that the view is not widely held in Silicon Valley.[25]

The military-commercial divide, in short, is not so clear. SpaceX, the prime representative of the commercial alt-space sector, has become a major defense contractor, with hundreds of millions of dollars in Pentagon business (including a contract announced in October 2020 for missile-tracking satellites). From the other direction, one might recall that both Lockheed and Northrop, for all their abundant experience as defense contractors, had an even longer history building commercial aircraft. At the time Lockheed developed Stealth it was also building the L-1011 commercial airliner, and several of Lockheed’s key Stealth engineers came to the project from the “white world,” the unclassified side of the company outside the Skunk Works.

The need for public-private collaboration persists because of that other lesson of Stealth, the need for long-term investment. Today’s literature on emerging technologies at times embraces the rhetoric of “disruption,” applying language from Silicon Valley startups to issues of national security.[26] This tendency no doubt reflects Silicon Valley's role in several of today's emerging technologies, such as AI. "Disruption," however, implies discontinuity, a sharp break, and it understates the time and effort required to develop new technologies. Directed-energy weapons, electromagnetic rail guns, microspacecraft, hypervelocity projectiles, and space-strike weapons have all been in the works for several decades—and their imminence often overhyped. This is not to say that such technologies won't appear, and the United States would indeed be wise to plan for them. But strategists should recognize that while emerging technologies may have revolutionary implications, their development is often a much longer-term evolution, not revolution.

Commercial firms focused on the next shareholder report remain unlikely to sink funds into a technology several decades away. If anything, to judge from the decline of industrial research labs, firms today are even less likely to make such investments.[27] Emerging technologies often require patience and a tolerance for risk that the private sector is unwilling to sustain. For Stealth, too, although both firms had invested company funds in the technologies that led to it, they remained wary of the financial risks. Lockheed's program almost died aborning after Skunk Works management judged it too risky and refused to pay for a key experiment; it was saved by discretionary funds from a manager outside the Skunk Works, in Lockheed's general aircraft division.

A corollary of long time frames: emerging technologies often come not from a single revolutionary breakthrough, but rather from a combination of incremental advances across several fields. Again, an analogy to nuclear weapons: the Manhattan Project succeeded not only because of the discovery of nuclear fission, but because it merged advances in many fields, including hydrodynamics (to design the explosive lenses for implosion), chemistry (for separation of radioactive elements), metallurgy (for casting of bomb components), and diagnostics (flash x-radiography to analyze key implosion experiments). Stealth similarly merged developments in radar diffraction theory, experimental radar test ranges, radar-absorbing materials, computer codes for scattering analysis, and fly-by-wire flight controls.

Emerging technologies may thus require someone to play matchmaker across technological fields. In the early 1970s the LRRD workshops performed this function; although Stealth was not a direct product of the LRRD meetings (it was already getting underway while they occurred), it reflected their mindset. The LRRD workshops helped the military think through the implications of emerging conventional technologies. The DOD has currently created a sequel, the Long-Range Research and Development Program Plan. The new LRRD should recognize not only that today's emerging technologies reflect decades of patient effort, whether in AI, quantum computing, or genomics, but also that breakthroughs are as likely to come from connections across technologies as from developments within a single field.

In turn, a corollary of the interconnections among technologies is the need for close attention to disciplinary dynamics—another continuity between Stealth and today's context. Emerging technologies will continue to encounter the friction between different science and engineering disciplines as well as the inertia inherent within individual disciplines. Quantum computing, for example, involves the confluence of physics, materials science, electrical engineering, and computer science, and members of each discipline will bring particular inclinations and approaches. Emerging technologies will require negotiation among these various disciplinary viewpoints.

Another constant: the importance of the shop floor. Although some new technologies, such as AI or cheap drones, are not as reliant on precision manufacturing, others, such as hypervelocity vehicles, are. The DOD's new LRRD includes a section on advanced manufacturing; it would help also to maximize manufacturing capability by ensuring that it is tightly integrated with engineering design.

One may ask whether U.S. manufacturing capability has dwindled, not only because of offshoring by industry (which separates design from production), but also through changes in engineering education. Today's engineers are far more proficient than their predecessors with computers, but most no longer get shop experience in high school or college. This is a loss. There is a possible countertrend, however, in the maker movement. A striking feature of Stealth is how many of its inventors played with model airplanes when they were children. Toys make technologists. If the United States wants to make new technologies in the future, it should give every child in the country (or at least every school) a 3-D printer today.

Emerging technologies will also continue to benefit from competition. Different institutions have different capabilities and philosophies depending on their disciplinary orientation and their history. Whether it was Lockheed vs. Northrop on Stealth or Los Alamos vs. Livermore on nuclear weapons, competition has entailed costly duplication but also brought different perspectives to bear, producing different solutions to the same technical problems. One might ask whether the United States has lost this element of competition because of corporate consolidation in the aerospace industry post-Cold War, and also because of the trend toward teaming big contracts, which dilutes the distinctive approach of a single firm. Subsequent Stealth competitions, however, on the F-22, F-35, and B-21, have seemed robust, at least judging by the responses of both winners and losers. The U.S. government has been sensitive to preserve competition: in 1998, after Lockheed Martin and Northrop Grumman announced that they planned to merge, the Justice and Defense Departments blocked it out of antitrust concerns.[28] The government should remain alert to trends that undermine competition.

The international roots of emerging technologies will also likely grow ever more important in an increasingly globalized world with widespread high-tech capabilities. Even when the United States enjoyed a stronger technological position internationally, it has always had competition; important contributions to Stealth came from the Soviet Union itself. With new technologies as likely to emerge abroad as at home, the United States should continue to encourage international scientific communication in order to keep abreast of new developments and inject new ideas. For Stealth, this occurred simply through the provision of translated foreign technical literature and the willingness of U.S. scientists and engineers to read it.

The international context is not limited to technology. U.S. analysts recognized the Soviet strategic reaction to Stealth because the translation of literature, and the willingness to read it, extended to work by Soviet military analysts as well as by Soviet scientists and engineers, and still more broadly to Soviet society and culture, through federal support of programs such as the Joint Publications Research Service.[29] This effort not only shed light on Soviet capabilities and intentions; it also gave U.S. analysts a new perspective on the implications of U.S. technologies.

Finally, although social attitudes towards weapons work have shifted since the Cold War, the need for secrecy has not changed—but secrecy will also continue to entail costs. We may again look to the past for lessons. A National Academy of Sciences report in 1982, almost 40 years ago, addressed the military's growing interest in high-tech weapons and the blurry line between open research and military applications in fields such as semiconductor manufacturing, optical science, and cryptography. (The study also noted that high-tech industrial capability had already spread globally). The report stressed that security-by-accomplishment was more effective than security-by-secrecy: open communication fostered innovation that would keep the United States ahead in the high-tech race. The committee specifically urged the government to "build high walls around narrow areas that are clearly defined."[30] The advice remains sound. Excessive secrecy stifles technical communication, deters potential workers, and increases costs; more basically, it runs counter to U.S. principles of democracy and civil liberties.

The Relevance of Stealth for Today's Emerging Technologies

In several respects, today's emerging technologies display continuity with the Cold War—not through simplistic analogies, but through particular factors that affected how technologies emerged in earlier times.[31] Although times have changed, and with them the technological and strategic context, some elements of the Cold War ecosystem that shaped the development of Stealth may still play a role: the advantages of competition, the need for long-term development and public-private collaboration, the inertia and friction of science and engineering disciplines, the role of advanced manufacturing, the benefits of international communication, and the effects of secrecy.

We may hope that another parallel applies: Stealth was not used in anger against its intended target, the Soviet Union. The Cold War ended with a fizzle, not a bang. Although some observers claim that the high-tech arms race induced the demise of the Soviet Union, the Soviet collapse had more immediate causes, from oil prices and ethnic nationalism to the war in Afghanistan and Poland's Solidarity movement. This suggests another possible lesson of Stealth: the need to beware of purely technological solutions to geopolitical problems.

We can meanwhile be confident that another lesson from Stealth still applies: the law of unintended consequences. Given the current variety of both emerging technologies and strategic threats, unintended consequences have become even more likely. For Stealth, the unexpected consequences included the effects on Soviet thinking, which suggests a corollary: the need to guard against mirror-imaging. The Soviets perceived the strategic import of Stealth and other emerging technologies differently because of their distinct history and ideology. And thus a final lesson: in addition to studying the implications of science and technology, strategists should consider the effects of culture, politics, and history.

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